HEAVY-FLAVORED STRANGE PENTAQUARK SEEMS NOT TO EXIST

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Abstract

Possible existence of a molecular-type heavy-flavored strange pentaquark is considered. No narrow state of such a type is shown to exist.

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I. INTRODUCTION

All the observable hadrons can be successfully classified at present as $\bar{q}q$ or qqq configurations. The challenging question of the existence of exotics remains unanswered. One of such an exotic states is the pentaquark: baryon containing 5 quarks $P_{\bar{Q}} \equiv \bar{Q}qqqq$ where $Q\,(=b,c)$ is a heavy quark and $q\,(=u,d,s)$ is a light one. Theoretical search for a pentaquark yielded controversial results. Its existence has been claimed in various approaches. Investigation of the pentaquark existence in the constituent quark model resulted in a confirmative conclusion provided 1) one of the light quarks is a strange one and 2) the binding color forces are assumed to be flavor-independent [1], [2]. Stated differently in the limit of "flavor-blind" color forces the $P_{\bar{Q}s}$ is expected to exist. However, the realistic breaking of the $SU(3)_F$ symmetry of QCD forces and, even more important, the motion of quarks being taken into account, the pentaquark proved to be unstable with respect to strong decay [3], [4].

Alternative approach to the issue is to consider the pentaquark as a bound state of Skyrme-type soliton (representing the nucleon) and a heavy meson. This model has been applied in the nonstrange sector only and the results obtained are far from being decisive. The bound state was shown to exist in both b- and c-sectors (corresponding to the $P_{\bar{b}}$ and $P_{\bar{c}}$ type pentaquarks) in the limit of the infinite heavy-quark mass [5]. At the same time corrections due to the finite mass of the heavy quark may make the pentaquarks states unbound [7].

Finally, a molecular-type pentaquark $P_{\bar{b}}$ state is predicted [6]. It is bound by the long-range one-pion-exchange forces ensuring its genuine molecular structure. However, these forces are not strong enough to bind a $P_{\bar{c}}$ pentaquark. In view of this controversial situation it is of interest to explore whether the molecular-type $P_{\bar{Q}s}$ pentaquark exists.

II. QUANTUM NUMBERS OF A MOLECULAR-TYPE STRANGE HEAVY-FLAVORED PENTAQUARK

Molecular-type hadron can be characterized by its particle content. The nonstrange $P_{\bar{b}}$ pentaquark is a loosely bound state of the $\bar{B}^*N$ system.. "Naive" extension of this approach to the system containing the nucleon and the bottom-flavored strange meson $\bar{B}_s(\equiv(\bar{b}s))$ fails: because of the $\bar{B}_s$-meson zero isospin it does not couple with the π-meson. The viable alternative is a molecular state comprising the (nonstrange) heavy quark H^*[1] and a hyperon Y. Two possibilities are conceivable depending on the total isospin of the system T. Consider first the $T=3/2$ case. Then the pentaquark-to-be necessarily has the $H-\Sigma$ particle content. The "effective" strength constant of the driving one-pion-exchange potential in the $T=3/2$ channel equals then $\nu = f_{\Sigma\Sigma\pi}\cdot f_{HH\pi}\cdot\gamma$, where γ is the spin factor. In the limit of the $SU(3)$ symmetry $f_{\Sigma\Sigma\pi}=2\alpha_P\, f_{NN\pi}$, where $f_{NN\pi}$ is the constant of the $NN\pi$ coupling and α_P is the $F/(F+D)$ ratio for the pseudoscalar mesons. The π-meson is known to couple to the isovector particles only and, hence, it is uncoupled from the isoscalar heavy quarks.

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[1]Since it does not result in confusion we hereafter will denote for notational brevity the heavy vector meson as H.

Introducing the constant g of the π-meson coupling to the constituent light quark we arrive at $f_{HH\pi} = g$. The coupling constant g is related also to the $NN\pi$ coupling constant: $g = 3/5\, f_{NN\pi}$. Combining all the enlisted factors we get the following expression for the "effective" strength constant of the one-pion-exchange in the $T = 3/2$ channel :

$$\nu_{H\Sigma} = 6/5\,\alpha_P\gamma\ \ f^2_{NN\pi}$$

It is instructive to compare this strength constant to its counterpart ν_{NN}in the NN system . The latter with the account of the spin-isospin factors reads

$$\nu_{NN} = 3\,f^2_{NN\pi}$$

The ratio of $\nu_{H\Sigma}$ and ν_{NN} strength constants is

$$\nu_{H\Sigma}/\nu_{NN} = 2/5\alpha_P\gamma$$

The α_P factor in the limit of the $SU(6)$ symmetry equals 0.4. Its value obtained in the Nijmegen potential equals $\alpha_P = 0.485$ [8]. The value of the spin factor γ depends on the spin and orbital momenta of the considered state. For the most favorable $^2S_{1/2} -^4 D_{1/2}$ configuration (see [6]) it is $\gamma = 2$. Thus we arrive at

$$\nu_{H\Sigma}/\nu_{NN} = 4/5\alpha_P$$

showing that $\nu_{H\Sigma} \approx 1/3\,\nu_{NN}$. One more factor which is important for binding is the reduced mass of the system. The ratio of reduced masses for the $H - \Sigma$ and NN systems equals

$$\frac{m_{H\Sigma}}{m_{NN}} = 2\,\frac{m_\Sigma}{m_N}\,\frac{1}{1 + m_\Sigma/m_H}$$

This ratio equals 1.55 (2.08) in the case of D- (B-) heavy meson. The increased reduced mass of the $H-\Sigma$ system as compared to the NN case still cannot overbalance the smallness of the effective strength constant $\nu_{H\Sigma}$ allowing to conclude safely that the molecular-type $H - \Sigma$ pentaquark with the $T = 3/2$ total isospin does not exist.

Alternative possibility is the $H - Y$ molecular state with the total isospin $T = 1/2$. This case comprises two coupled channels: $H - \Lambda$ and $H - \Sigma$. As it was stated above the configuration which is the most favorable from the point of view of binding by the one-pion-exchange has the $J^\pi = 1/2^-$ quantum numbers corresponding to the $^2S_{1/2} -^4 D_{1/2}$ coupled channels. Thus we arrive at the system of 4 coupled Schrödinger equations which can be written in the matrix form

$$\frac{d^2\phi}{dr^2} = \mathcal{K}^2\,\phi + 2mV\phi \tag{1}$$

where ϕ is the column of wave functions with the following numeration of channels: (1) $H - \Lambda$ (S-wave); (2) $H - \Lambda$ (D-wave); (3) $H - \Sigma$ (S-wave); (4) $H - \Sigma$ (D-wave) and $\mathcal{K}^2$ is the diagonal 4×4 matrix of c.m.s. momenta squared (plus the matrix of centrifugal potentials):

$$\mathcal{K}^2 = \begin{bmatrix} \kappa^2_{\Lambda H} & & & \\ & \kappa^2_{\Lambda H} + 6/r^2 & & \\ & & \kappa^2_{\Sigma H} & \\ & & & \kappa^2_{\Sigma H} + 6/r^2 \end{bmatrix} \tag{2}$$

The c.m.s. momenta squared in eq.(2) for the kinetic energy E in the $H\Lambda$ channel are equal to $\kappa^2_{\Lambda H} = 2m_{\Lambda H} \cdot E$ and $\kappa^2_{\Sigma H} = 2m_{\Sigma H}(E + \Delta m)$, where Δm is the mass difference of the Σ- and Λ-hyperons ($\Delta m = m_\Sigma - m_\Lambda \approx 76$ MeV) and m_{YH} ($Y = \Lambda, \Sigma$) is the reduced mass in the corresponding channel. In eq.(2) m is the diagonal 4×4 matrix with the $m_{\Lambda H}$ and $m_{\Sigma H}$ elements. Finally, V is the matrix of driving forces reading:

$$V^\pi = V_0 \left[T \otimes C_s \, \tilde{y}_0(m_\pi r) + T \otimes C_t \, \tilde{y}_2(m_\pi r) \right] \tag{3}$$

where V_0 is the potential unit introduced in [9]

$$V_0 = \frac{m^3_\pi}{12\pi} \frac{g^2}{f^2_\pi} \tag{4}$$

where g is the constant of the $\pi-$meson coupling to the constituent quark and f_π is the constant of the $\pi-$meson decay ($f_\pi \approx 132$ MeV). In eq.(3) $\tilde{y}_l$ ($l = 0, 2$) are the regularized at small x's radial functions

$$\tilde{y}_0(x) = y_0(x) - y_0(\lambda x) - (\lambda - 1) \exp(-\lambda x) \ , \tag{5}$$

and

$$\tilde{y}_2(x) = y_2(x) - \lambda^3 y_2(\Lambda x) - \exp(-\lambda x) \, \frac{(\lambda^2 - 1)(\lambda x + 1)}{2x} \tag{6}$$

where $y_{0,2}(x)$ are the spherical modified Bessel functions

$$y_0(x) = \exp(-x)/x; \ \ y_2 = \exp(-x)/x \cdot (1 + 3/x + 3/x^2)$$

and $\lambda = \Lambda/m_\pi$, with Λ being a cut-off parameter (see below). The $C_{s(t)}$ matrix contains spin coefficients for the central (tensor) components of the one-pion-exchange forces:

$$C_s = \begin{bmatrix} -2 & 0 \\ 0 & 1 \end{bmatrix}; \ C_t = \begin{bmatrix} 0 & -1 \\ -1 & \sqrt{2} \end{bmatrix}$$

Finally, T is the matrix of isospin coefficients which in the limit of the $SU(3)$ symmetry limit reads

$$T = \begin{array}{c|c|c} & H - \Lambda & H - \Sigma \\ \hline H - \Lambda & 0 & -10/3\,(1 - \alpha_P) \\ H - \Sigma & -10/3\,(1 - \alpha_P) & -20/3\,\alpha_P \\ & & \end{array} \tag{7}$$

where α_P is defined above.

III. BINDING OF A MOLECULAR-TYPE PENTAQUARK

Complexity of the system under consideration make application of numerical methods mandatory. Before proceeding to the numerical solution of the system (1) let us consider either conditions for emerging of a loosely bound state are favorable. To this end we apply the criterion for the appearance of a zero-energy level in a system where a central force is operative [10]. For the Yukawa forces under consideration the parameter to be investigated reads

$$s = 0.5953 \cdot 2\bar{m}\gamma \, \frac{V_0}{m_\pi^2}$$

where $\bar{m}$ is the reduced mass of the system and γ is the spin-isospin factor. The only component of the system under consideration where the Yukawa forces are operative is the S-wave $H - \Sigma$ channel. To make conclusions more transparent we compare the $s_{\Sigma H}$ value to the (reference) value of its NN counterpart s_{NN}:

$$\frac{s_{\Sigma H}}{s_{NN}} = \frac{\gamma_{\Sigma H}}{\gamma_{NN}} \cdot 2\frac{m_\Sigma}{m_N} \cdot \frac{1}{1 + m_\Sigma/m_H} \tag{8}$$

The spin-isospin $\gamma_{\Sigma H}$ factor equals the product of corresponding elements of the C_s and T matrices:

$$\gamma_{\Sigma H} = 2 \cdot 20/3 \cdot \alpha_P$$

In the same notations the γ_{NN} equals

$$\gamma_{NN} = 25/3$$

Substituting these expressions into eq.(8) we arrive at

$$\frac{s_{\Sigma H}}{s_{NN}} \approx \frac{4\alpha_P}{1 + m_\Sigma/m_H}$$

This ratio depends upon the mass of the heavy meson m_H and for the case of the D- (B-) meson it is

$$s_{\Sigma H} \approx s_{NN} \cdot 1.0 \ (1.3) \tag{9}$$

The value of $s_{NN} \approx 0.33$ is known to be smaller than that required for the emergence of a zero-energy level ($s \geq 1$) [10], nevertheless existence of the deuteron and the virtual bound state in the ${}^1S_0$ channel suggests it as a benchmark for the appearance of a loosely bound state. Inspection of (9) shows that the conditions for the binding of the $H - \Sigma$ pair are at least not worse than in the NN system.. It should be emphasized, however, that this conclusion should be considered rather as guide. Indeed, the pentaquark-to-be spends part of the time in the $H - \Lambda$ channel where the interaction is absent. The resulting attraction is weakened and the existence of a bound state can be explored by the numerical solution of the system (1).

The equations to be solved involve two parameters controlling the strength of the interaction. First, it is the constant g of the π-meson coupling to the constituent quark which determines the value of the potential unit (4). The value of g can be extracted from the well-known constant of the pseudovector $NN\pi$ coupling:

$$g = 3/5\, f_{NN\pi} \tag{10}$$

where $f^2_{NN\pi}/4\pi = 0.08$. However, the coupling of the π-meson to a constituent quark bound in the heavy H-meson may be altered by the presence of the heavy quark. Another parameter affecting the strength of the one-pion exchange is the formfactor cut-off Λ (see (5) and (6)). The larger is Λ the more are potentials peaked at small x's and the stronger is the resulting potential. The value of Λ is poorly known: in different models of the NN interaction it varies from 0.8 GeV to 1.5 GeV. Note, however, that variations of g and Λ affect the strength of the interaction in the same direction: when either of these parameter increases the one-pion-exchange potential becomes more strong.

The system (1) up to apparent modifications describes as well the NN interaction in the ${}^3S_1 -{}^3 D_1$ state. In this case the isotopic T matrix (7) becomes a diagonal one with all the matrix elements equal to -25/3, and the system (1) splits into two identical 2×2 subsystems. The value of g which follows from (10) equals $g \approx 0.6$ and the corresponding value of the potential unit $V_0 \approx 1.3$ MeV [9]. The deuteron binding energy $\epsilon_D \simeq 2.2$ MeV is reproduced with g value increased by 15% (30%) for the values of the cut-off parameter $\Lambda = 1500$ MeV (1200 MeV). Note that these values of the potential-strength parameters are somewhat higher than those obtained in [9].

With the same set of parameters we solved eqs. (1) for the considered $B\Lambda - B\Sigma$ system to find out the existence of a loosely bound state. According to expectations the binding energy increases with both g and Λ growing (see fig.1). Due to the small value of binding energy the mass of the state is close to the sum of masses of its components: $m \approx m_B + m_\Lambda \approx 6.4$ GeV. At the same time the bound state of the $D\Lambda - D\Sigma$ system was not found for any reasonable values of the potential strength parameters.

In spite of this encouraging result the $B\Lambda - B\Sigma$ bound state seems not to be observable as a resonance structure. Indeed, the hadronic composition of this object when translated into the quark content reads $(b\bar{q}) - (sqq)$. It implies that the found baryonic state can recombine into the tightly bound heavy baryon (bqq) (or its strange counterpart (bsq)) with the emission of mesons built of light quarks. The mass of the lightest bottom-flavored baryon Λ_b is about 5.75 GeV [11]. Because of large energy release (about 700 MeV) the width of such a decay will be large, and any resonance-like structure will be completely smeared off. A state with the genuine pentaquark quantum numbers (i.e. the $(\bar{b}sqqq)$ configuration) would correspond to a (loosely bound) state in the $\bar{B}\Lambda - \bar{B}\Sigma$ system. However, due to negative G-parity of the π-meson the one-pion-exchange potential in such a system will have the sign opposite to that in the $B\Lambda - B\Sigma$ system. Thus the considered mechanism will generate repulsion and apparently no bound $\bar{B}\Lambda - \bar{B}\Sigma$ state will exist.

IV. CONCLUSION

We have considered possible existence of a heavy-flavored pentaquark with strangeness $P_{\bar{Q}s} \equiv (\bar{Q}sqqq)$. As it was stated in the Introduction such a multiquark state definitely does

not exist as a system of 5 quarks bound by the color QCD forces. In the approach where a pentaquark is considered as a bound state of a soliton (nucleon) and a heavy meson the problem has not been explored. Two circumstances should be taken into account. First, even in the nonstrange sector this model does not yield any decisive conclusions. Second, the soliton-based model is ill-suited to the investigation of the $P_{\bar{Q}s}$ pentaquark. Indeed, in this model the hyperon treated as a strange counterpart of the nucleon is already considered as a bound state of the Skyrme-type soliton (nucleon) and the K-meson [12]. Then the consistent description of the heavy meson and the hyperon interaction would imply the investigation of a three-body system comprising the heavy meson, the K-meson and the nucleon (soliton). Alternative soliton-based approach where the pentaquark is a bound state of the nucleon and the (isoscalar) B_s meson would imply that the long-range one-pion exchange drops out and the interaction is controlled by the forces of smaller range with the entailing ambiguities related to the short-distance structure of the soliton.

We have investigated the existence of a molecular-type pentaquark. One-pion exchange proves to be strong enough to produce a loosely bound state in the $B\Lambda - B\Sigma$ system with the quantum numbers $J^\pi(T) = 1/2^-(1/2)$. However, because of the quark content $(b\bar{q}) - (sqq)$ of this bound state it can decay rapidly into a bottom-flavored baryon Λ_b or its strange analogue with the emission of light-quark mesons. Because of the large energy release the width of such a decay will be rather large precluding possible observation of a resonance-like structure. Thus we can conclude that the investigation of the heavy-flavored strange pentaquark $P_{\bar{Q}s}$ in various theoretical approaches favor the conclusion that such an exotic multiquark state is either non existing or is unobservable.

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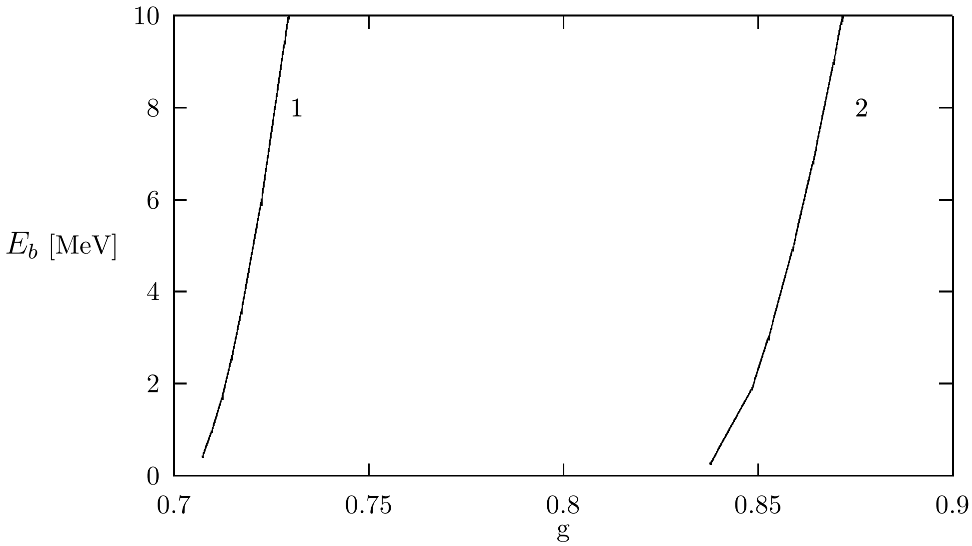
FIGURES

Dependence of the binding energy E_b in the $\Lambda H - \Sigma H$ system with the $J^\pi(T) = 1/2^-(0)$ quantum numbers upon the formfactor cut-off Λ and the potential parameter g. Curve 1(2) corresponds to $\Lambda = 1500$ (1200) MeV.


10
8
6
4
2
0
E_b [MeV]
0.7
0.75
0.8
0.85
0.9
g
1
2